Contamination-Mitigating Epoxy Coatings for Aircraft Leading Edges

Christopher J. Wohl[1], Michelle H. Shanahan[2], Alexandra J. Bosh[3], Joseph G. Smith Jr.[1], Ronald K. Penner[4], John W. Connell[1], Emilie J. Siochi[1]

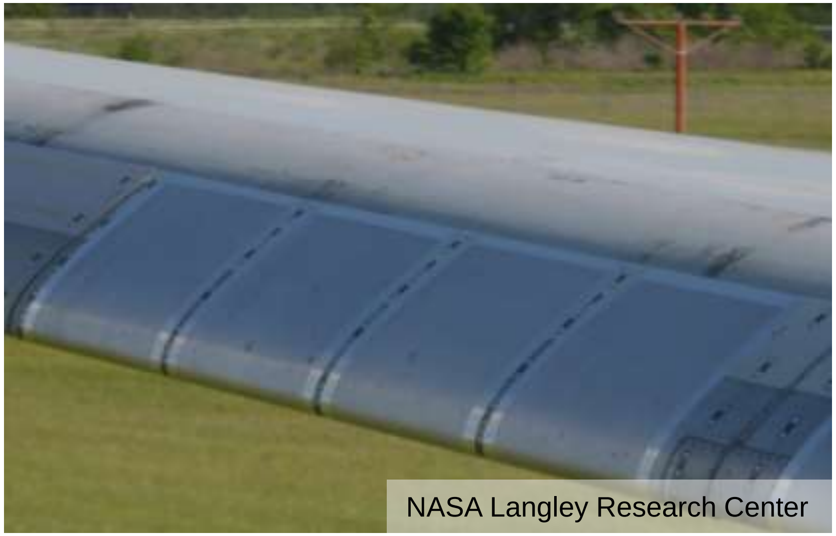
[1]NASA Langley Research Center, Hampton, VA 23681
[2]National Institute of Aerospace, Hampton, VA 23666
[3]NIFS Intern, NASA Langley Research Center, Hampton, VA 23681
[4]Science and Technology Corporation, Hampton, VA 23666

39th Annual Meeting of the Adhesion Society

February 21-25, 2016

Leading Edge Surface Contaminants

Insect Residues

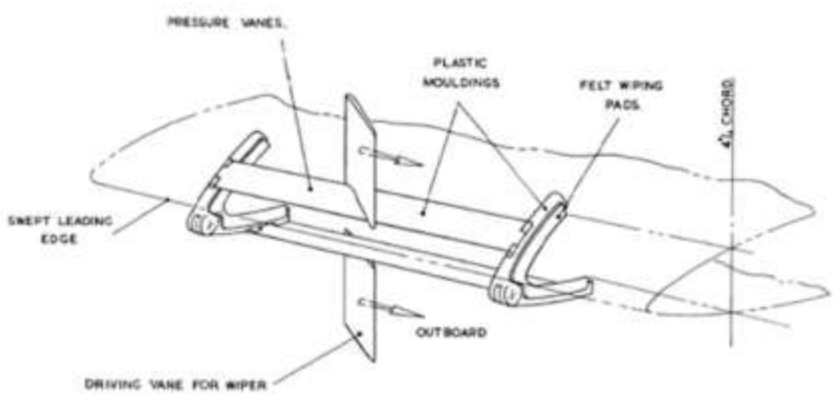

NASA Langley Research Center

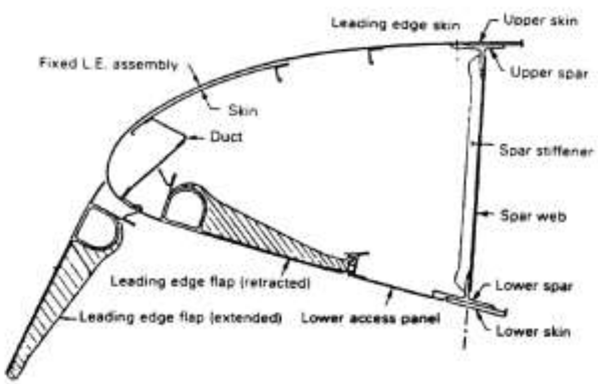
In-Flight Icing


NASA Glenn Research Center

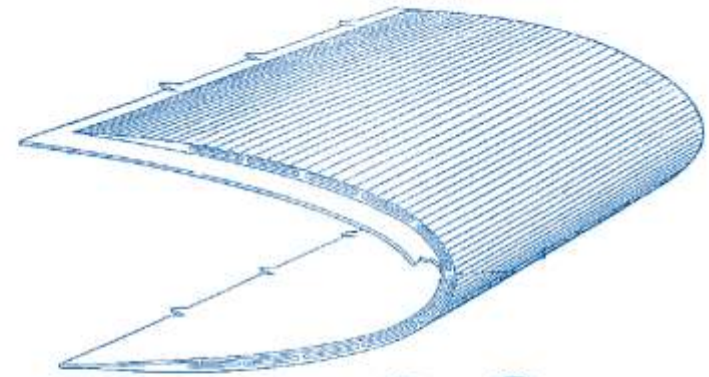
Mitigation Strategies

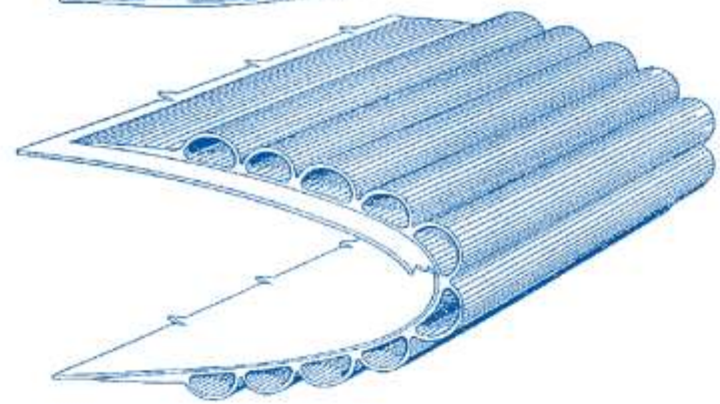
Insect Residues





In-Flight Icing

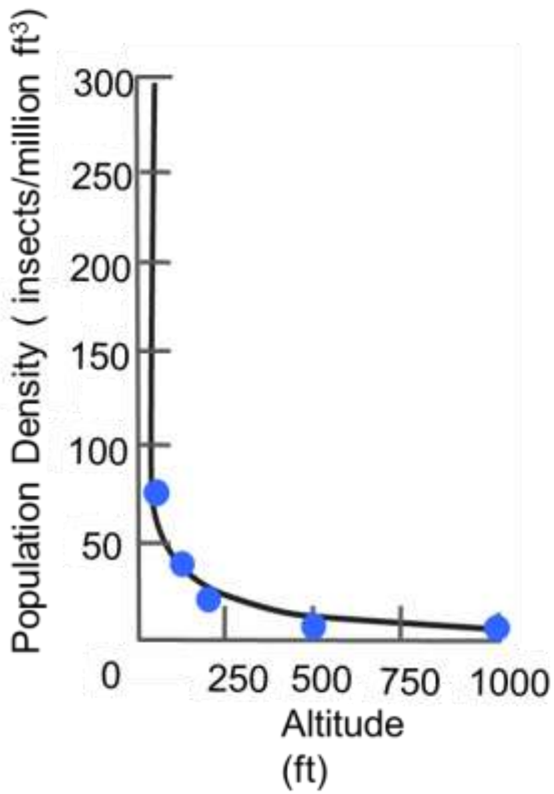




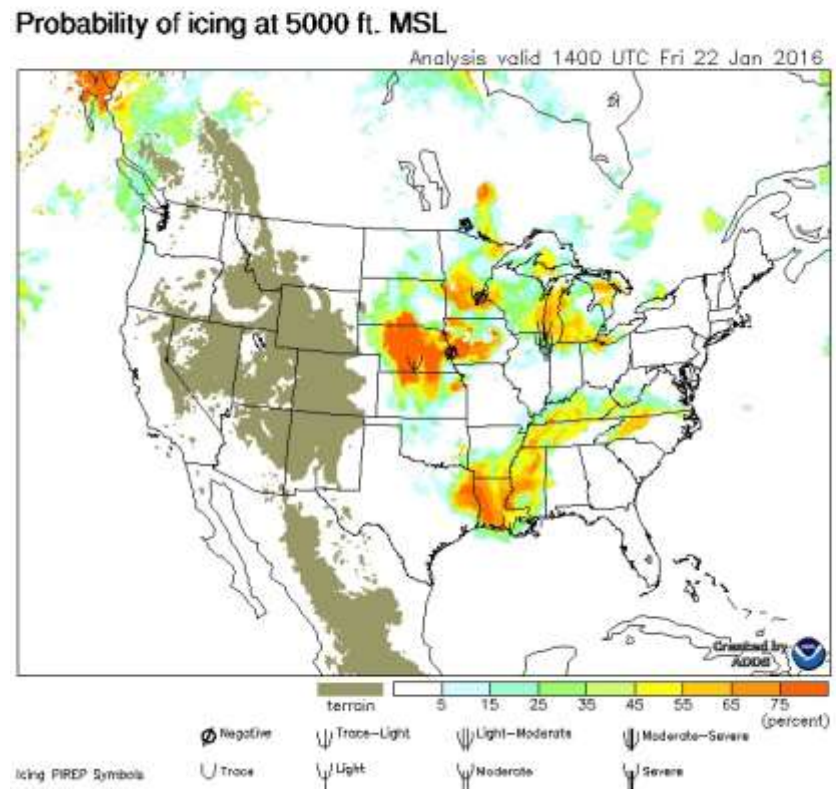
Coleman, W.S. “Boundary Layer and Flow Control”, ed. G.V. Lachman, Pergamon Press, 1961, pp. 682-747.
Rudolf, P. K. C. “High-lift Systems on Commercial Subsonic Airliners,” NASA Conference Report, 1996, CR-4746.
Landsberg, B. “Aircraft Icing,” Air Safety Foundation, AOPA Safety Advisor, Weather Number 1, 2002.

Mitigation Strategies

Insect Residues



In-Flight Icing



Bragg, M.G. and Maresh, J.L. AIAA Paper no. 84-2170, 1984.

Commonality of Insects and Ice

Accretion of insect residues or ice impacts airflow

- Both occur in-flight and are a product of the environment
- Both change airflow properties adversely

Insect residue and ice accretion can be mitigated

- Active mitigation strategies consume energy and increase vehicle weight
- Passive mitigation strategies are:
  - Insects → tolerance
  - Ice → avoidance

Differences Between Insects and Ice

Accretion of insect residues or ice impacts airflow

- Insect residue accretion will increase drag on future aircraft
- Ice accretion is a current safety issue
- Insect residue accretion occurs during take-off and landing
- Ice accretion can occur in a variety of flight profile locations

Insect residue and ice accretion can be mitigated

- Insect residue accretion is intermittent
- Ice accretion is continuous under icing flight conditions
- Roughness mitigates insect residue accretion
- Roughness worsens ice adhesion

Contaminant Mitigation Compromise

Can we generate a single coating formulation that would exhibit adhesion mitigation of both insect residues and in-flight icing?

Surface Chemical Change

Surface Topography Change

IAMC-5A Modified COTS Epoxy	IAMC-4 Research Epoxy	IAMC-3 Research Urethane
IAMC-5B Modified COTS Epoxy/1 Filler		
IAMC-5 Modified COTS Epoxy/2 Fillers		

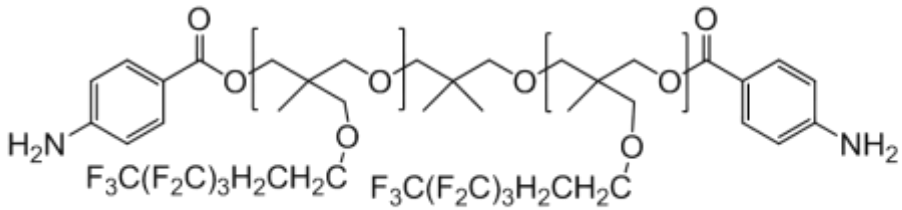
Images of the coatings

These epoxy coatings were generated to evaluate this question

Epoxy Coating Compositions

Coating Description

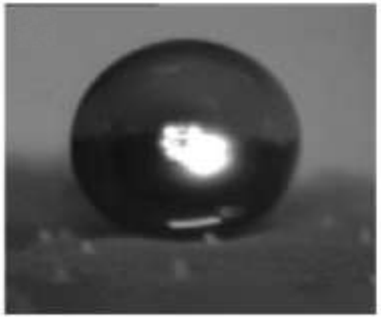
Coating	Type	Filler(s), Loading (wt%)	Filler Diameter (nm)	Roughness (Ra, µm)
IAMC-3	Urethane	None	1	8.8 ± 4.0
IAMC-4	Research Epoxy	None	1	4.8 ± 1.6
IAMC-5	Epoxy	MoS_2 (1.25%) SiO_2 (3.75%)	2,000 7	62.2 ± 19.5
IAMC-5A	Epoxy	None	1	9.6 ± 2.0
IAMC-5B	Epoxy	SiO_2 (10%)	7/10	395.5 ± 60.1



Fluorinated Aliphatic Ether (FAE)

*FAE was incorporated in all formulations at 1 wt%

Environmentally Responsible Aviation



Screen commercial and experimental materials using contact angle goniometry

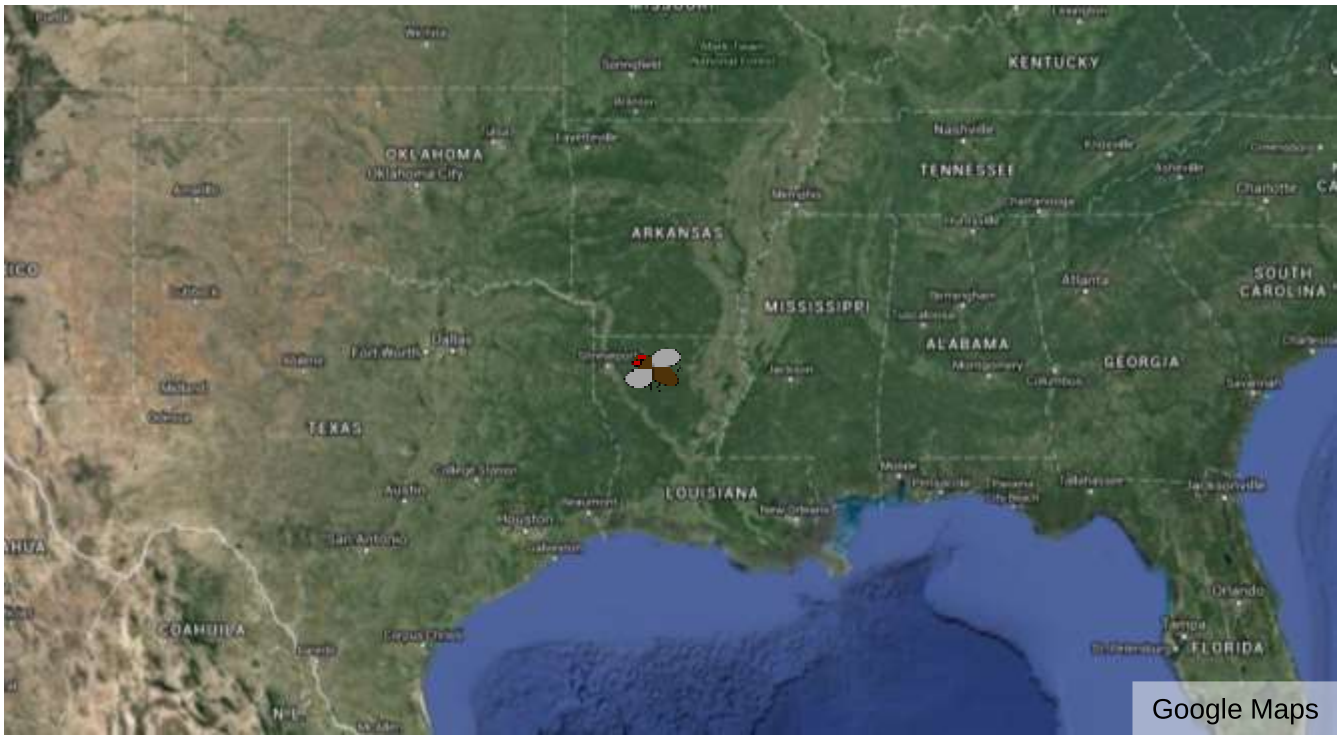
Downselect promising coatings for wind tunnel testing

The Boeing Company

Flight test candidate coatings down-selected from wind tunnel tests

EcoDemonstrator Flight Testing

- April 29 – May 10, 2015 in Shreveport, LA



EcoDemonstrator Flight Testing

April 29 – May 10, 2015 in Shreveport, LA

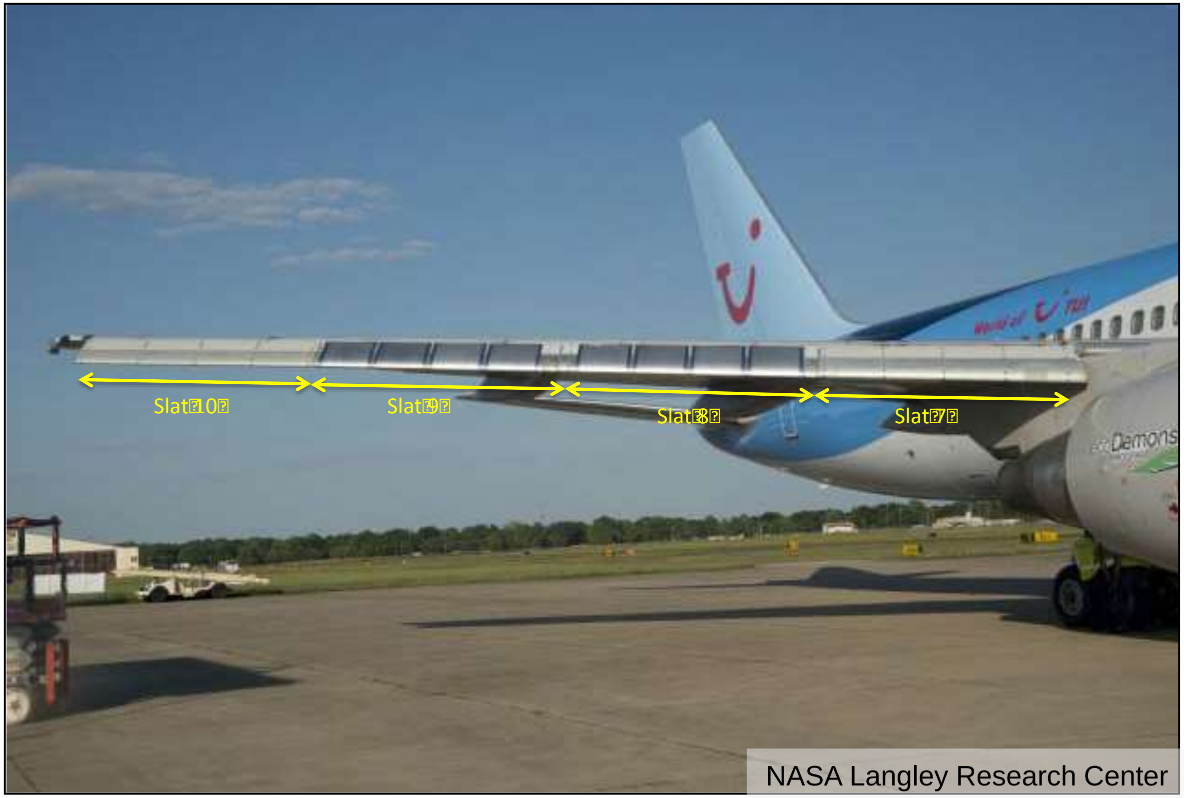
EcoDemonstrator Flight Testing

Test panels installed on leading edge slats

The Boeing Company

EcoDemonstrator Flight Testing

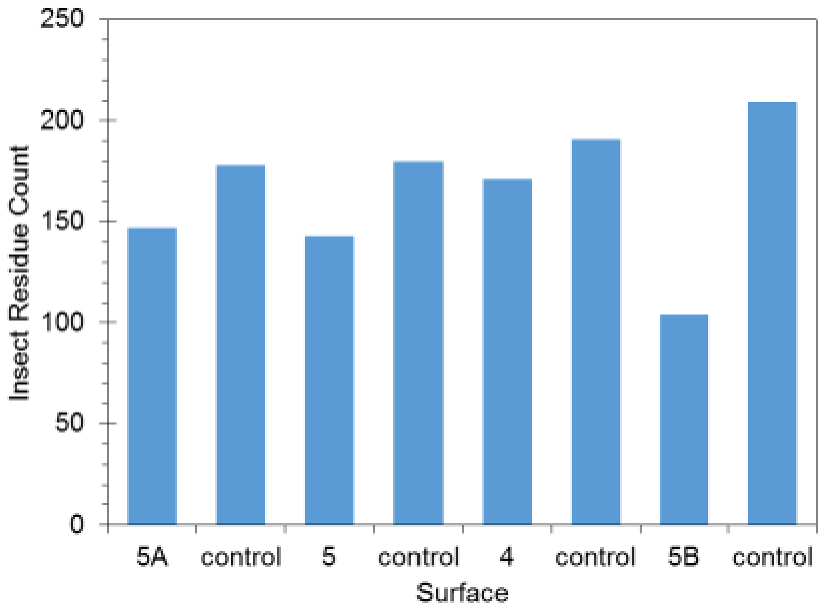
Test panels installed on leading edge slats



Residue Counts

Approach to Data Analysis

Insect Residue Count for Flight Test 6



% Reduction Relative to Local Control Surfaces

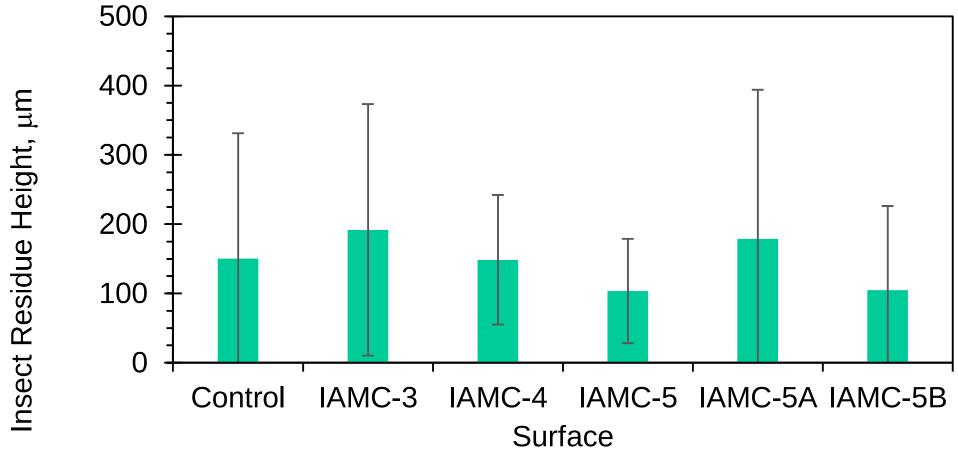
Coating	Rank Tally for all Flights			
	# 1	#2	#3	#4
IAMC 3	0	0	1	4
IAMC 4	1	0	1	2
IAMC 5	4	3	2	0
IAMC 5A	0	3	4	2
IAMC 5B	5	2	1	1

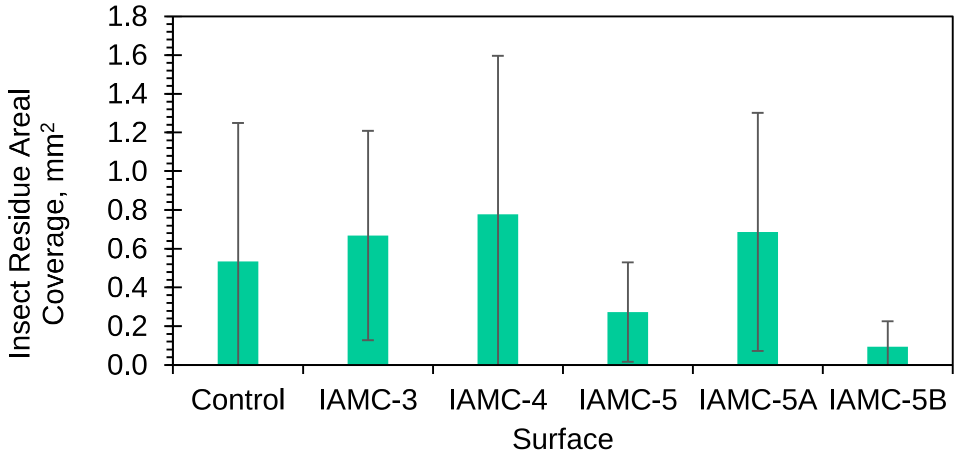
Performance Rank (PR)

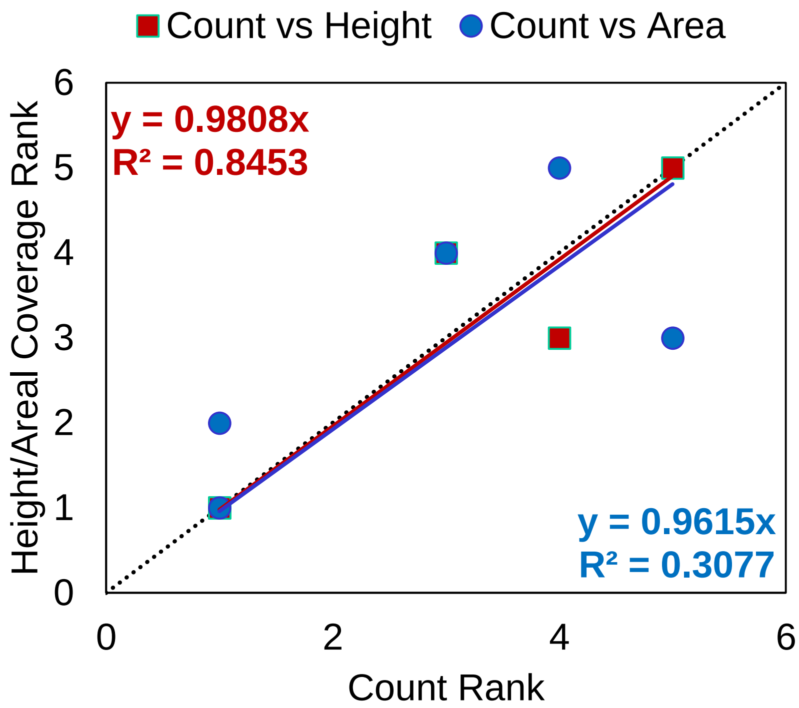
$$\boxed{PR = \frac{\sum n * Rank}{\# \, of \, Flights}}$$

n= number of instances at a particular rank

Approach to Data Analysis



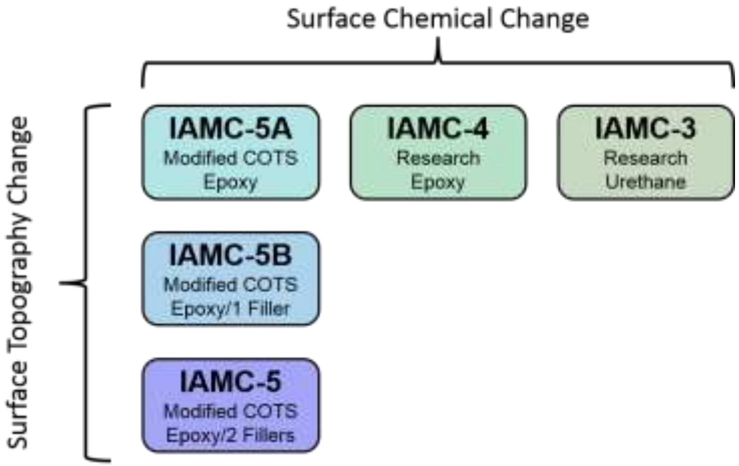




Coating Performance-Insects

Langley Research Center

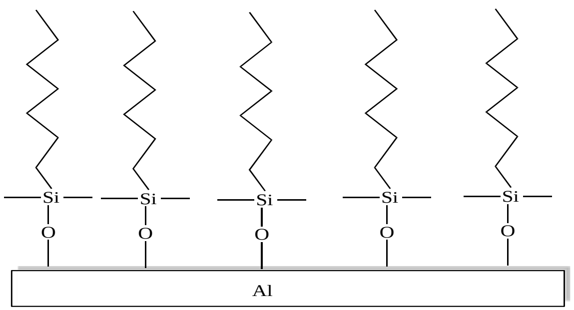
Rank	Insect Residue Study	Ice Adhesion Study
1	IAMC-5	
2	IAMC-5B	
3	IAMC-4	
4	IAMC-5A	
5	IAMC-3	

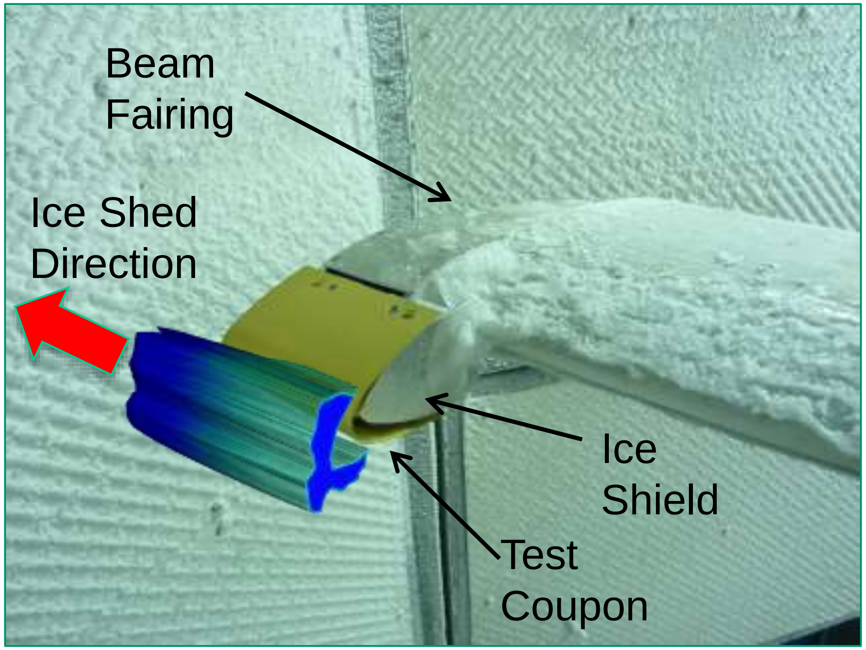


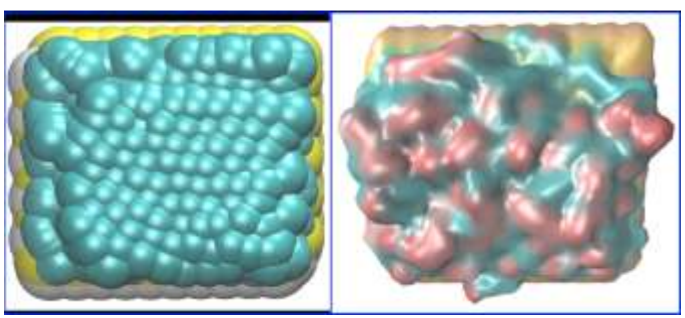
NARI Icing Project

*NARI: NASA Aeronautics Research Institute

Seedling study to investigate fundamentals of ice adhesion at a molecular level experimentally and computationally







Smith Jr., J. G. et al. “Hydrogen Bonding Surface for Ice Mitigation” NASA Technical Memorandum, 2014, 218291.

Adverse Environment Rotor Test Stand

Pennsylvania State University

Testing performed under simulated icing conditions

- FAR Part 25/29 Appendix C icing envelope
  - Super-cooled water injected into test chamber
  - Tests conducted at -8 to -16 ºC
  - Icing cloud density (liquid water content, LWC) of 1.9 g/cm^3
  - Water droplet mean volumetric diameter of 20 μm

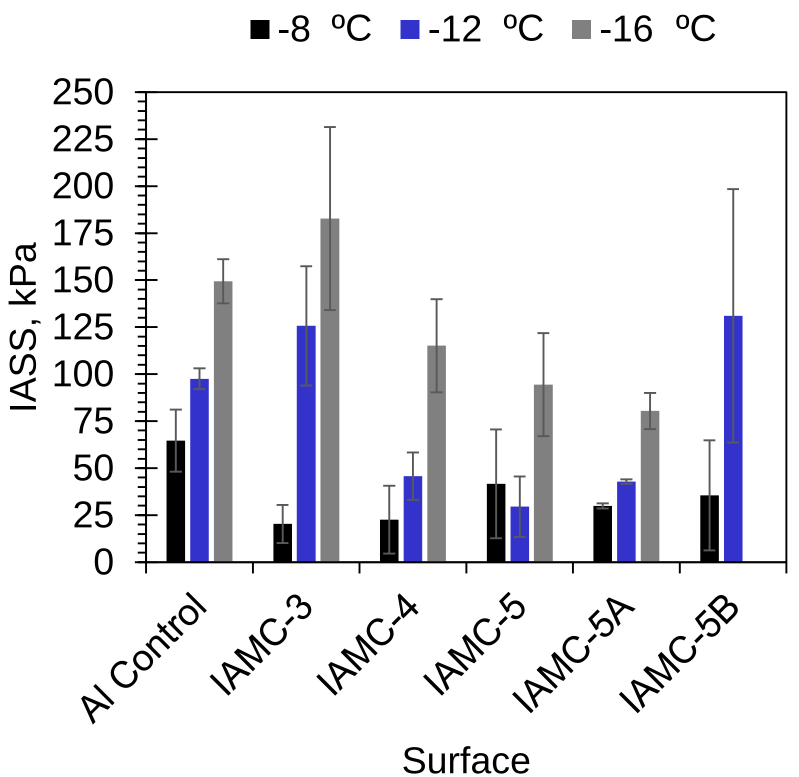

PSU, Jose Palacios

Ice accumulation and subsequent shedding enabled determination of ice adhesion shear strength (IASS)

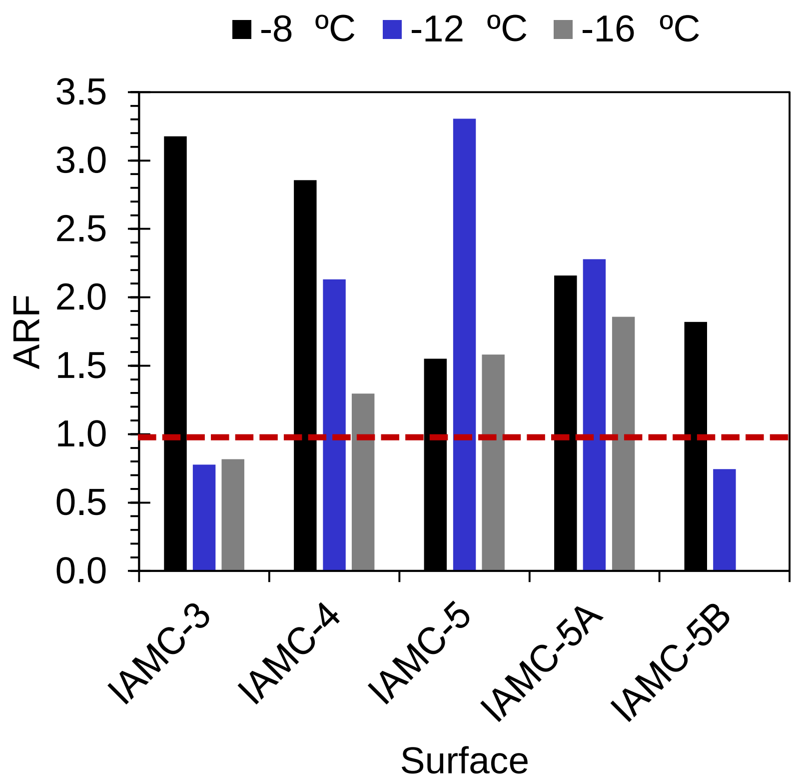
Soltis, J. et al., "Evaluation of Ice Adhesion Strength on Erosion Resistant Materials", 54th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Apr 8-11, 2013, Boston, MA, AIAA 2013-1509.

AERTS Results

Ice Adhesion Shear Strength



Adhesion Reduction Factor

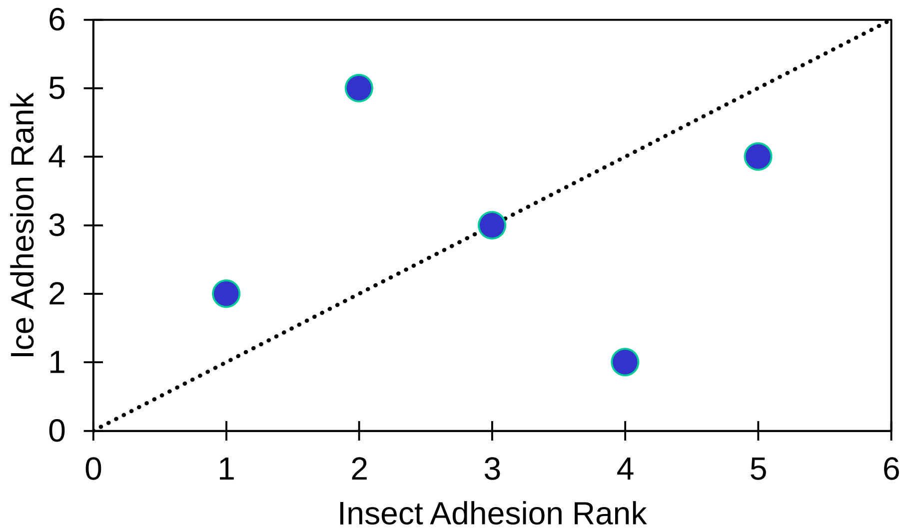


$$ARF = \frac{IASS\ of\ Al\ Surface}{IASS\ of\ Coated\ Al\ Surface}$$

Coating Performance-Ice Adhesion

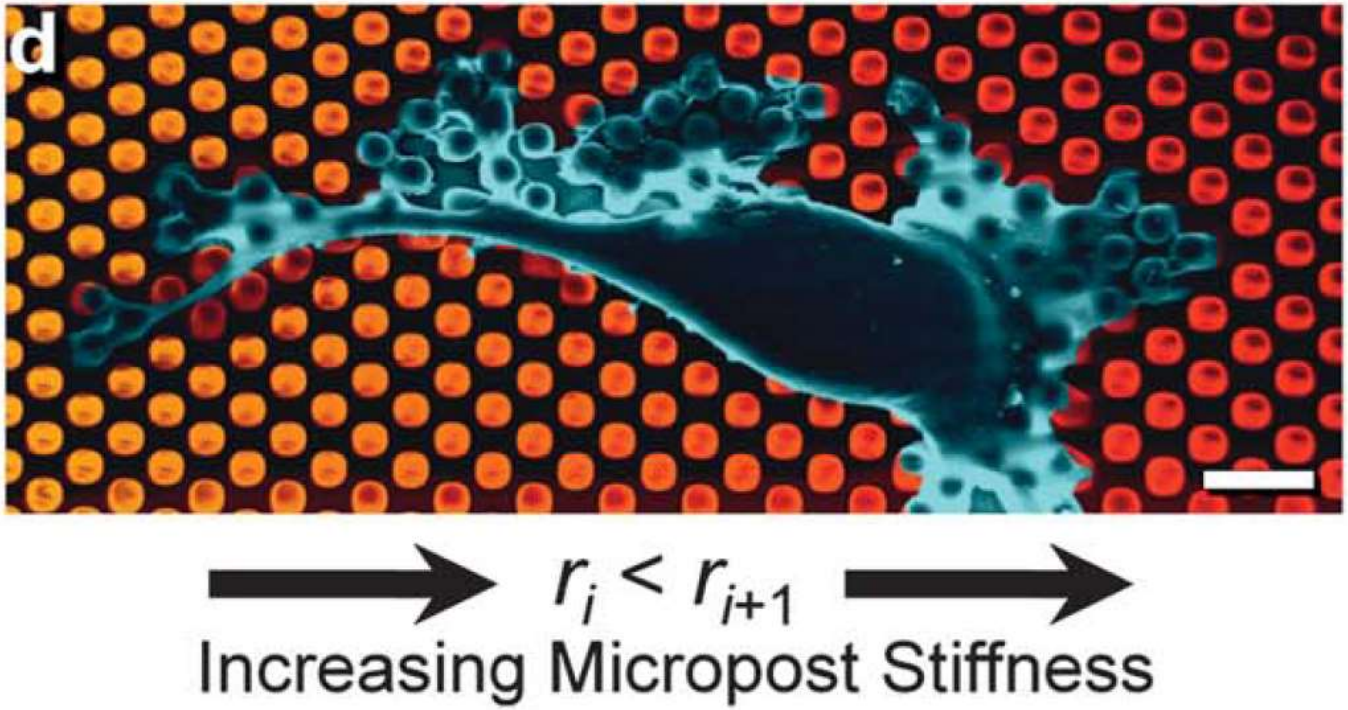
Langley Research Center

Rank	Insect Residue Study	Ice Adhesion Study (-12 ºC)
1	IAMC-5	IAMC-5A
2	IAMC-5B	IAMC-5
3	IAMC-4	IAMC-4
4	IAMC-5A	IAMC-3
5	IAMC-3	IAMC-5B



Can We Do Better?

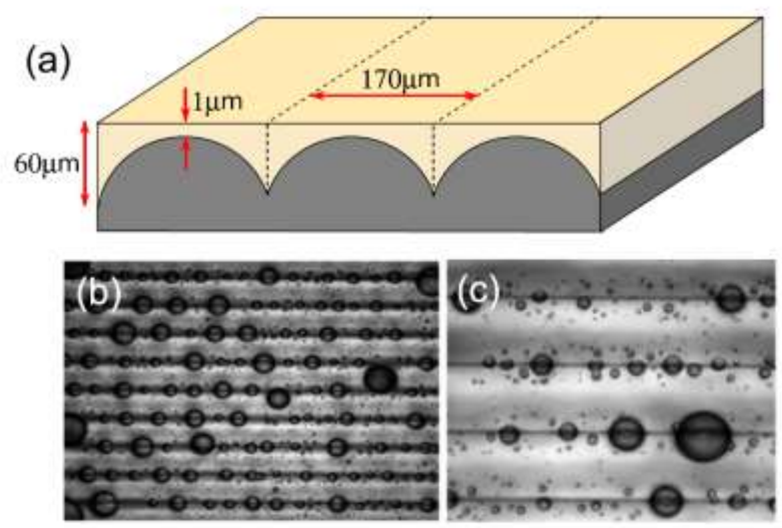
Durotaxis: a form of cell migration in which cells are guided by rigidity gradients.



Sochol, Ryan D., et. al, Soft Matter, 2011, 7, 4606.

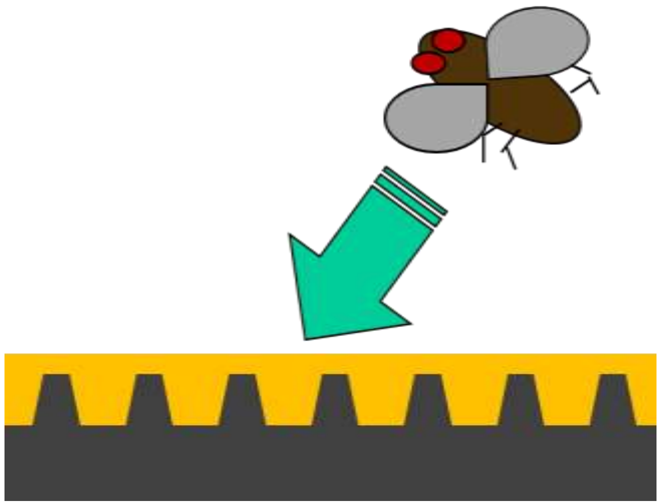
Surfaces with Durotaxis-like Phenomena

Droplet motion in the absence of active locomotion on low modulus PDMS-coated stress-gradient surface.

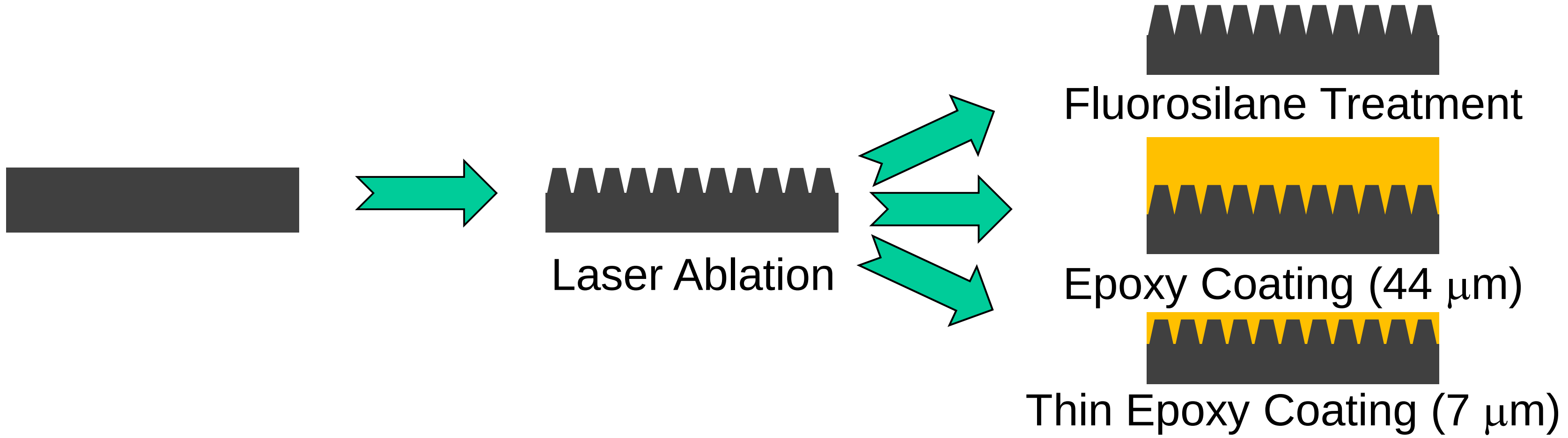


Style, Robert W., et. al, *PNAS,* 2013, 110(13), 12541.

Can this be translated to insect impact events?



Substructure Topographical Modification

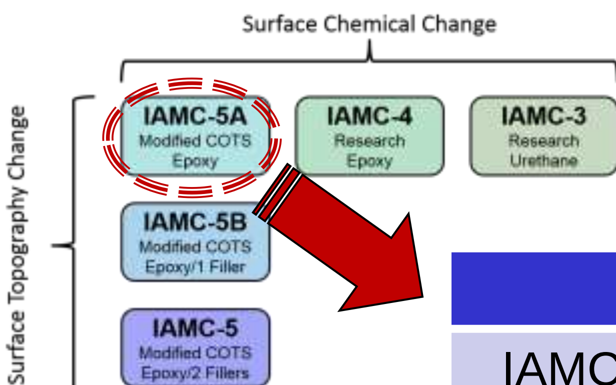


	Roughness (Ra, μm)			
Pulse Energy (μJ)	Laser Ablated (LA)	LA + Fluorosilane	LA + Epoxy	LA + Thinned Epoxy
0	0.19	0.26	0.85	---
20	1.16	1.00	0.26	0.23
50	2.07	2.02	0.25	0.37
70	2.87	2.80	0.38	0.36
87	2.86	2.77	0.34	0.31

Fruit Fly Impact Experiments

Pneumatic Insect Delivery Device

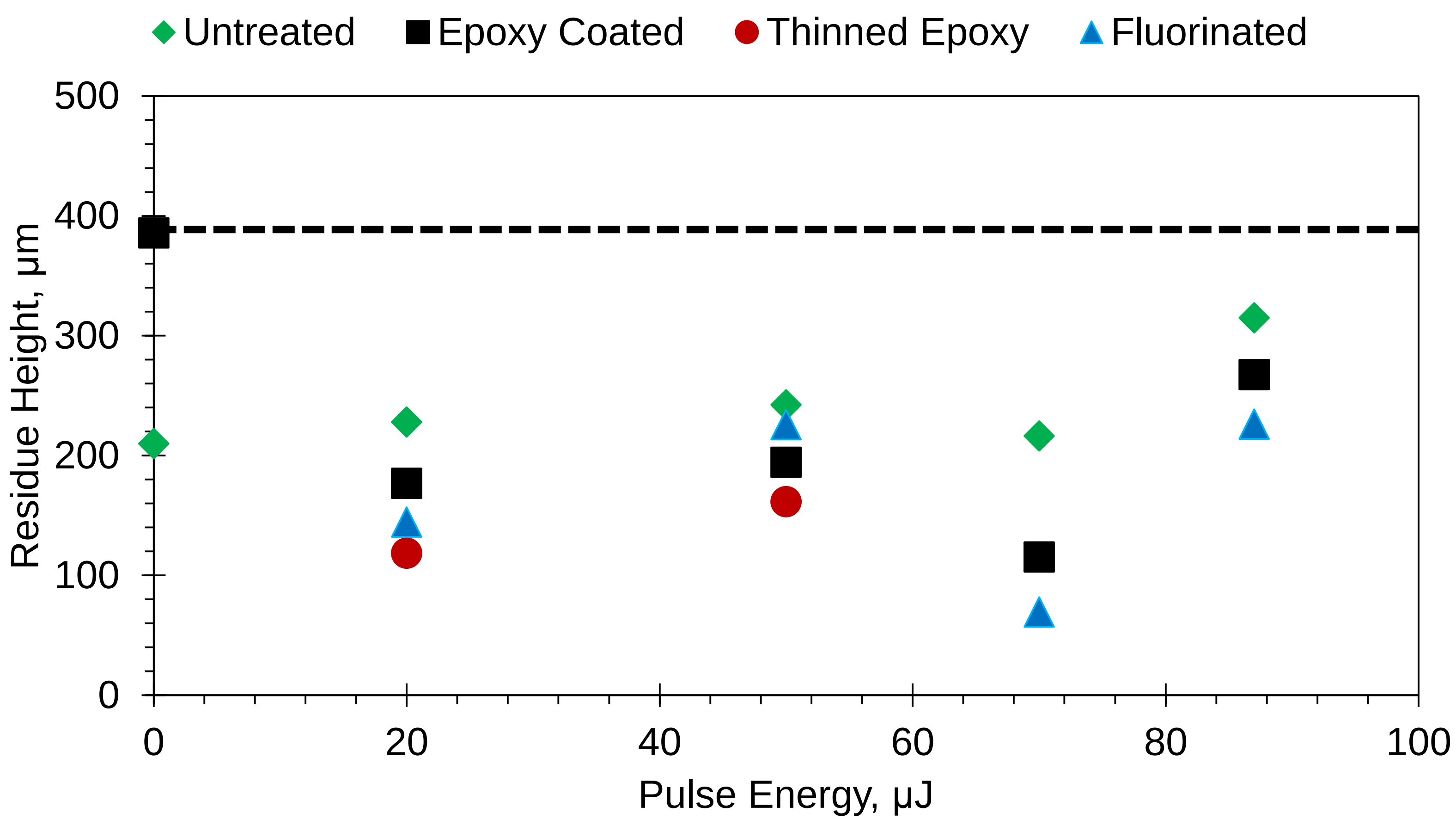
High Speed Photography



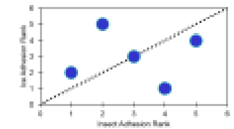
	Insect Rank	Ice Rank
IAMC-5A	4	1

Fruit Fly Impact Experiments

Langley Research Center

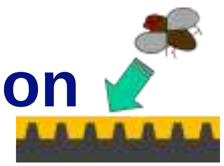


Summary and Conclusions



An example of “one size does not fit all”

- Coatings exhibited desired behavior during flight testing
- These same coatings exhibited mixed performance regarding ice adhesion testing
- Coating features have different effects on insect residues and ice



The idea of sub-surface topographical modification opens up a new research arena

- Initial results suggest that, for insect residue adhesion, the forces are strong enough at impact for translation through epoxy layer

It will be important to balance contaminant adhesion coating and aeronautics requirements

Acknowledgements

EcoD

- NASA LaRC: Keith Harris, Jim Fay, Mike Alexander, Paul Bagby
- Boeing EcoD Team

NARI Ice Team:

- Pennsylvania State University: Jose Palacios and Taylor Knuth
- NASA GRC: Richard “Eric” Kreeger
- North Dakota School of Mines and Technology: Kevin Hadley and Nick McDougall

Durotaxis discussion

- Yale: Eric Dufresne and Kate Jensen